UNITED STATES PATENT APPLICATION

OFDM SYSTEM WITH PER SUBCARRIER PHASE ROTATION

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TECHNICAL FIELD

The invention relates generally to wireless communications and, more particularly, to multicarrier wireless communications.

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BACKGROUND

One of the problems that must often be overcome in a wireless communication system to ensure reliable, high quality communication is multipath fading. In a wireless channel, it is often the case that a transmitted signal will reach a receiver by more than one path. That is, the signal may reach the receiver by a direct path from the transmitter

15 and also by one or more other paths that involve signal reflection from objects or structures in the surrounding environment. Because the lengths of the different paths will typically be different, the corresponding signal components received at the receiver will usually have different phases. Sometimes the phasing of the received signal components will result in partial or full cancellation of the signal at the receiver. This

20 loss of signal at the receiver is known as multipath fading. In some situations, the fading will be frequency selective. That is, the fading will be more pronounced at some frequencies than at others. In other situations, however, the fading may occur in a relatively uniform fashion over a larger bandwidth. This may be referred to as non-frequency selective or "flat" multipath fading. Many techniques exist for effectively

25 dealing with frequency-selective multi-path fading. However, there is a need for methods and structures that are capable of addressing flat multipath fading, particularly in systems that utilize multicarrier communication techniques.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a block diagram illustrating an example orthogonal frequency division multiplexing (OFDM) transmitter arrangement in accordance with an embodiment of the present invention;

5   Fig. 2 is a block diagram illustrating an example OFDM transmitter arrangement that may be used in a MIMO based system in accordance with an embodiment of the present invention;

Fig. 3 is a table illustrating example subcarrier preambles that may be used in a MIMO based transmitter arrangement having two transmit antennas in accordance with

10   an embodiment of the present invention;

Fig. 4 is a flowchart illustrating an example method for use in generating an OFDM transmit signal in accordance with an embodiment of the present invention; and

Fig. 5 is a block diagram illustrating an example OFDM transmitter arrangement that may be used in a MIMO based system in accordance with another

15   embodiment of the present invention.

DETAILED DESCRIPTION

In the following detailed description, reference is made to the accompanying

20   drawings that show, by way of illustration, specific embodiments in which the invention may be practiced. These embodiments are described in sufficient detail to enable those skilled in the art to practice the invention. It is to be understood that the various embodiments of the invention, although different, are not necessarily mutually exclusive. For example, a particular feature, structure, or characteristic described

25   herein in connection with one embodiment may be implemented within other embodiments without departing from the spirit and scope of the invention. In addition, it is to be understood that the location or arrangement of individual elements within each disclosed embodiment may be modified without departing from the spirit and scope of the invention. The following detailed description is, therefore, not to be taken

30   in a limiting sense, and the scope of the present invention is defined only by the

appended claims, appropriately interpreted, along with the full range of equivalents to which the claims are entitled. In the drawings, like numerals refer to the same or similar functionality throughout the several views.

Fig. 1 is a block diagram illustrating an example orthogonal frequency division multiplexing (OFDM) transmitter arrangement 10 in accordance with an embodiment of the present invention. As illustrated, the transmitter arrangement 10 may include one or more of: a phase shift unit 12, an inverse fast Fourier transform (IFFT) 14, a guard interval (GI) addition unit 16, a transmitter 18, and an antenna 20. The phase shift unit 12 receives a number of modulation data symbols X_n at an input thereof. The modulation data symbols may be received from, for example, a mapper/modulator that maps input data bits based on a predetermined modulation scheme. Any of a wide range of different modulation schemes may be used including, for example, binary phase shift keying (BPSK), quadrature phase shift keying (QPSK), 16 quadrature amplitude modulation (16 QAM), 64 QAM, and/or others. A serial to parallel converter or interleaver may be also be used to form a parallel input into the phase shift unit 12. Each of the modulation data symbols X_n received by the phase shift unit 12 may be associated with, for example, a corresponding subcarrier of an OFDM signal to be generated and transmitted into the wireless channel.

The phase shift unit 12 applies a subcarrier dependent phase shift to each of the modulation symbols X_n input thereto. For example, with reference to Fig. 1, the phase shift unit 12 applies a phase shift ϕ_1 to symbol X_1 that is dependent upon the subcarrier associated with the symbol X_1, a phase shift ϕ_2 to symbol X_2 that is dependent upon the subcarrier associated with the symbol X_2, and so on. The phase shifted data symbols are then applied to the IFFT 14 which converts the symbols from a frequency domain representation to a time domain representation. The GI addition unit 16 then adds a guard interval onto the time domain signal to form the OFDM symbol to be transmitted. The OFDM symbol is then input to the transmitter 18 which, among other things, upconverts and power amplifies the signal for transmission from the antenna 20. Any type of antenna 20 may be used including, for example, a dipole, a patch, a helical antenna, an array, and/or others.

The transmitter arrangement 10 is intended to be used in a multiple transmit antenna system. That is, two or more of such arrangements 10, each having its own antenna, are to be implemented within a transmitter. The subcarrier dependant phase shift sequences used for the different antennas in the multiple antenna system will typically be different. By providing these subcarrier dependent phase shifts to the modulation symbols, a wireless channel that is displaying flat multipath fading characteristics may be converted into a frequency selective fading channel that can then be dealt with in a known manner.

As described above, the phase shift unit 12 applies a subcarrier dependent phase shift to each of the modulation data symbols input thereto. A variety of different approaches may be used for determining the phase shifts based on subcarrier. In one approach, for example, a phase term that is linearly related to the corresponding subcarrier frequency may be used, as follows:

$$\phi_n = \alpha \, f_n$$

where f_n is the subcarrier frequency of the nth subcarrier relative to the channel center frequency and α is a constant. Other methods for generating phase terms that are linearly related (or non-linearly related) to subcarrier frequency may alternatively be used.

In at least one embodiment, features of the invention are implemented in a multiple input multiple output (MIMO) based multicarrier system. In a MIMO based system, multiple transmit antennas are used to transmit into a wireless channel (multiple input) and multiple receive antennas are used to receive the signal from the wireless channel (multiple output). MIMO systems are characterized by their ability, in the presence of rich multipath, to significantly increase the peak throughout that would otherwise be achievable in a single input, single output (SISO) system, without increasing the frequency bandwidth. Fig. 2 is a block diagram illustrating an example transmitter arrangement 30 that may be used in a MIMO based system in accordance with an embodiment of the present invention. As shown, the transmitter arrangement

30 includes: a first IFFT 32, a first GI addition unit 34, and a first transmitter 36 that are associated with a first transmit antenna 38 and a second IFFT 42, a second GI addition unit 44, and a second transmitter 46 that are associated with a second transmit antenna 48. In addition, the arrangement 30 includes a phase shift unit 40 that is associated with

5   the second transmit antenna 48. A plurality of modulation data symbols X_n are received and are directed along paths associated with each of the two transmit antennas 38, 48. In the first path (associated with antenna 38), no subcarrier dependent phase shifting takes place. The data symbols X_n are first processed by the first IFFT 32 which transforms them from a frequency domain representation to a time domain

10   representation. A guard interval is then added to the time domain signal by the GI addition unit 34. The resulting signal is then input to the transmitter 36 for transmission from the first transmit antenna 38. In the second path (associated with antenna 48), the modulation data symbols X_n are first processed by the phase shift unit 40 which applies a subcarrier dependent phase shift to each of the symbols. The phase

15   shifted symbols are then processed by the second IFFT 42, the second GI addition unit 44, and the second transmitter 46, and are thereafter transmitted from the second transmit antenna 48.

By inserting subcarrier dependent phase factors into the modulation data symbols associated with at least one of the two transmit antennas 38, 48, a wireless

20   channel suffering from flat fading can be converted into a frequency selective channel that can be dealt with in a known manner. In an alternative arrangement, a different subcarrier-dependent phase sequence may be applied for each of the two transmit antennas 38, 48. Although shown with two transmit antennas 38, 48 in the illustrated embodiment, it should be appreciated that MIMO based transmitter arrangements

25   having more than 2 transmit antennas may alternatively be used. In such an arrangement, at least one of the transmit antennas should apply subcarrier dependent phase shifts to the corresponding modulation symbols, as described above. In one possible implementation, subcarrier dependent phase shifts are applied for more than one transmit antenna in the multi-antenna arrangement, with a different subcarrier

30   dependent phase sequence being used for each antenna.

In at least one MIMO based embodiment of the invention, a set of orthogonal or quasi-orthogonal spatial weights are applied to modulation symbols across groups of tones that are within a coherence bandwidth (B) of one another. Coherence bandwidth refers to a range of frequencies within which frequency components tend to all fade in a

5   similar or correlated fashion in a system. In one possible phase shift approach, for example, a phase shift of 360/B (degrees) is applied from tone to tone across each group of B tones associated with at least one of the transmit antennas in a multi-antenna arrangement. Fig. 3 is a table 50 illustrating the subcarrier preambles that may be used to implement this approach in a MIMO based transmitter arrangement having two

10   transmit antennas in accordance with an embodiment of the present invention. As illustrated, the preambles 52 associated with the subcarriers of a first antenna (ANTENNA 1) are not phase shifted, while the preambles 54 associated with the subcarriers of a second antenna (ANTENNA 2) are shifted in a subcarrier dependent manner. The subcarriers are divided into three different coherence bands

15   (COHERENCE BAND A, COHERENCE BAND B, and COHERENCE BAND C) that are each approximately a coherence bandwidth wide. For each of the coherence bands, the subcarriers are phase shifted from subcarrier to subcarrier by $2\pi/B$ radians (or 360/B degrees). The pattern is then repeated for the next coherence band. This technique can be extended for use in a system having 3 or more antennas. For example, the phase

20   may be increased from $e^{j2\pi/B}$ to $e^{j(M-1)2\pi/B}$ on the M*th* transmit antenna. Other techniques may alternatively be used. The motivation for the above-described techniques are as follows. A frequency selective fade is approximately constant over a coherence bandwidth. In order to reliably transmit the preamble over a coherence bandwidth, it is best to rotate it uniformly over all spatial directions, so that at least

25   some of the received tones experience a good signal level. As an exact coherence bandwidth value if often unattainable, an approximation of the coherence bandwidth may be used in the above-described techniques.

In another approach for use in a MIMO based system, the same signal may be transmitted on different antennas by successively delaying the signal on each antenna.

30   That is, the signal transmitted from the M*th* transmit antenna is cyclically delayed by

(M-1)D time samples with respect to the first antenna, where D is the cyclic delay. This technique is capable of making the transmitted signal appear omnidirectional. The cyclic delay may also be adapted to the channel delay spread. For example, a smaller cyclic delay may be used with lower delay spreads and a larger cyclic delay may be used with higher delay spreads. In general, delay diversity can be proprietary and does not require standardization.

One of the problems that arises when using multiple transmit antennas that each transmit the same signal (such as in a MIMO based system) is that a directional antenna pattern often results. In at least one embodiment of the present invention, subcarrier dependent phases are selected for subcarriers associated with at least one transmit antenna in a multiple transmit antenna arrangement in a manner that results in an omni-directional aggregate radiation pattern over all of the subcarriers. Although the radiation pattern of each individual subcarrier cannot typically be made omni-directional using this technique, the aggregate pattern over all of the subcarriers can be made to be substantially omni-directional in an open loop transmit diversity system. As before, subcarrier dependent phases may be applied to a single antenna or to multiple antennas (using different subcarrier dependent phase sequences) in the multi-antenna arrangement.

Fig. 4 is a flowchart illustrating an example method 70 for use in generating an OFDM transmit signal in an OFDM system in accordance with an embodiment of the present invention. The method 70 may be used to generate transmit signals in both MIMO based systems and non MIMO based systems. In a MIMO based system, the method 70 may be used, for example, to generate an OFDM signal for transmission from one (or more than one) of a plurality of transmit antennas. First, modulation symbols are acquired that are to be used to generate an OFDM signal (block 72). The modulation symbols include at least a first symbol and a second symbol, but may include any number of symbols. Each of the modulation symbols may correspond to a subcarrier of the OFDM symbol. A first phase shift is applied to the first symbol that is dependent upon a subcarrier associated with the first symbol (block 74). A second phase shift is applied to the second symbol that is dependent upon a subcarrier

associated with the second symbol (block 76). An inverse discrete Fourier transform (e.g., a fast Fourier transform, etc.) is subsequently performed on a group of symbols that includes the phase shifted first and second symbols (block 78). In at least one embodiment, all of the modulation symbols that are to be used to generate the OFDM

5   signal are subjected to a subcarrier dependent phase shift and are included in the group of symbols that are transformed. After the inverse discrete Fourier transform is performed, a guard interval may be added to the resulting signal. The signal may then, for example, be up-converted to an RF transmit frequency, power amplified, and transmitted from an antenna or other form of transducer.

10   Fig. 5 is a block diagram illustrating an example OFDM transmitter arrangement 80 in accordance with another embodiment of the present invention. The transmitter arrangement 80 may be used, for example, in a system implementing MIMO techniques. As illustrated, the transmitter arrangement 80 may include one or more of: a forward error correction (FEC) coder 82, a mapper 84, a spatial stream interleaver 86,

15   a steering unit 88, a plurality of inverse fast Fourier transform (IFFT) units 90, 92, 94, and a plurality of antennas 96, 98, 100. The FEC coder 82 receives data at an input thereof and codes the data based on a predetermined error code. Any of a variety of different error codes may be used. The mapper 84 maps the coded data based on a predetermined modulation scheme (e.g., BPSK, QPSK, 16 QAM, 64 QAM, and/or

20   others) to generate a serial stream of modulation symbols at an output thereof. The spatial stream interleaver 86 then interleaves the serial stream of modulation symbols into a plurality of spatial streams 102. Any number of spatial streams may be generated in this fashion. The steering unit 88 receives the spatial streams output by the spatial stream interleaver 86 and steers the associated symbols to a number of antenna paths

25   104, 106, 108 in a predetermined manner. In at least one embodiment, the steering unit 88 achieves its function by multiplying input data (received within the serial streams 102) by a steering matrix. Each of the antenna paths 104, 106, 108 includes a corresponding IFFT 90, 92, 94 to convert corresponding modulation symbols from a frequency domain representation to a time domain representation. Although illustrated

30   as IFFT's, it should be appreciated that any type of discrete Fourier transform may be

used. Each of the antenna paths 104, 106, 108 leads to a corresponding antenna 96, 98, 100. As before, any type of antennas may be used. Other circuitry may also be included between each IFFT and its corresponding antenna (e.g., a guard interval addition unit, an RF transmitter, etc.). Any number of antenna paths may be used. The

5   number of spatial streams 102 may or may not be equal to the number of antenna paths 104, 106, 108.

In at least one embodiment of the present invention, the steering unit 88 is used to provide subcarrier dependent phase terms to the data symbols that will be output to at least one of the antenna paths 104, 106, 108. The subcarrier dependent phase terms

10   may be selected as described previously. In at least one approach, an additional matrix multiplication may be performed within the steering unit 88 to provide the phase terms to the desired modulation symbols. For example, if the steering matrix to be used in a particular implementation is represented as V^*, then the phase terms may be introduced by modifying the steering matrix as follows:

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$$V^{(k_{sc})} = D\left(f_{k_{SC}};\tau\right) V^*$$

where

$$D(f;\tau) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & e^{j2\pi f\tau_1} & 0 \\ 0 & 0 & e^{j2\pi f\tau_2} \end{bmatrix}$$

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where $V^{(k_{sc})}$ is the modified steering matrix, k_{sc} is the subcarrier index, $f_{k_{sc}}$ is the subcarrier frequency, and τ_1 and τ_2 are delays associated with corresponding antenna paths. In the arrangement 80 of Fig. 5, if the number of spatial streams 102 is equal to the number of antenna paths, then the steering matrix V^* will be the identity matrix. In

25   such a case, the arrangement 80 of Fig. 5 will be similar to the arrangement 30 of Fig. 2. Alternatively, the steering matrix V^* may be any fixed unitary matrix; for example, the Walsh matrix previously displayed.

The linear phase term as just described is applied after the fixed steering matrix $\mathbf{V}^*$. In this case, the phase term $e^{j2\pi f_{k_{SC}}\tau_i}$ is applied to the i'*th* antenna. In a MIMO system, it is possible to have more transmit antennas than spatial streams. The number of rows of $\mathbf{V}$ is the number of transmit antennas and the number of columns is the number of spatial streams. Now, in addition to applying the phasing per antenna, it is also possible to apply phases per spatial stream. In this case, we have the reverse order of $\mathbf{V}^*$ and $\mathbf{D}$:

$$\mathbf{V}^{(k_{sc})} = \mathbf{V}^* \mathbf{D}\left(f_{k_{SC}};\tau\right)$$

and the dimension of square matrix $\mathbf{D}(f;\tau)$ is now the number of spatial streams (rather than the number of transmit antennas).

Although various embodiments have been described above in the context of MIMO based systems that typically have multiple receiver antennas, it should be appreciated that the above described principles may also be implemented in systems that use multiple transmit antennas and only a single receive antenna.

The inventive techniques and structures may be used in any of a wide variety of different wireless devices, components, and systems. For example, in various embodiments, features of the invention may be implemented within laptop, desktop, palmtop, and/or tablet computers having wireless networking functionality, personal digital assistants (PDAs) having wireless networking functionality, cellular telephones and other handheld wireless communicators, pagers, network interface cards (NICs) and other network interface structures, radio frequency integrated circuits, and/or other devices, systems, and components.

It should be appreciated that the individual blocks illustrated in the block diagrams herein may be functional in nature and do not necessarily correspond to discrete hardware elements. For example, in at least one implementation, two or more of the blocks within a block diagram (e.g., Fig. 1) may be realized in software within a single (or multiple) digital processing device(s). The digital processing device(s) may

include, for example, a general purpose microprocessor, a digital signal processor (DSP), a reduced instruction set computer (RISC), a complex instruction set computer (CISC), a field programmable gate array (FPGA), an application specific integrated circuit (ASIC), and/or others, including combinations of the above. Hardware, software, firmware, and/or hybrid implementations may be used.

In the foregoing detailed description, various features of the invention are grouped together in one or more individual embodiments for the purpose of streamlining the disclosure. This method of disclosure is not to be interpreted as reflecting an intention that the claimed invention requires more features than are expressly recited in each claim. Rather, as the following claims reflect, inventive aspects may lie in less than all features of each disclosed embodiment.

Although the present invention has been described in conjunction with certain embodiments, it is to be understood that modifications and variations may be resorted to without departing from the spirit and scope of the invention as those skilled in the art readily understand. Such modifications and variations are considered to be within the purview and scope of the invention and the appended claims.